LONG-TERM OPERATING EXPERIENCE FOR THE ATLAS SUPERCONDUCTING RESONATORS

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Abstract

Portions of the ATLAS accelerator have been operating now for over 21 years. The facility has accumulated several million resonator-hours of operation at this point and has demonstrated the long-term reliability of RF superconductivity. The overall operating performance of the ATLAS facility has established a level of beam quality, flexibility, and reliability not previously achieved with heavy-ion accelerator facilities. The actual operating experience and maintenance history of ATLAS are presented for ATLAS resonators and associated electronics systems. Solutions to problems that appeared in early operation as well as current problems needing further development are discussed.

1 INTRODUCTION and FACILITY DESCRIPTION

In the middle 1970's, a development project in superconducting RF technology began at Argonne National Laboratory. The initial work focused on the development of superconducting helical resonant cavities matched to a velocity of approximately 5% of the speed of light (0.05c). The difficulties of phase stabilizing such a mechanically unstable resonator soon became apparent. The project activity soon focused on a three-gap split-ring structure invented in the middle 1970's[1] and culminated in the first acceleration of a heavy ion for nuclear physics research using superconducting RF technology in 1978.

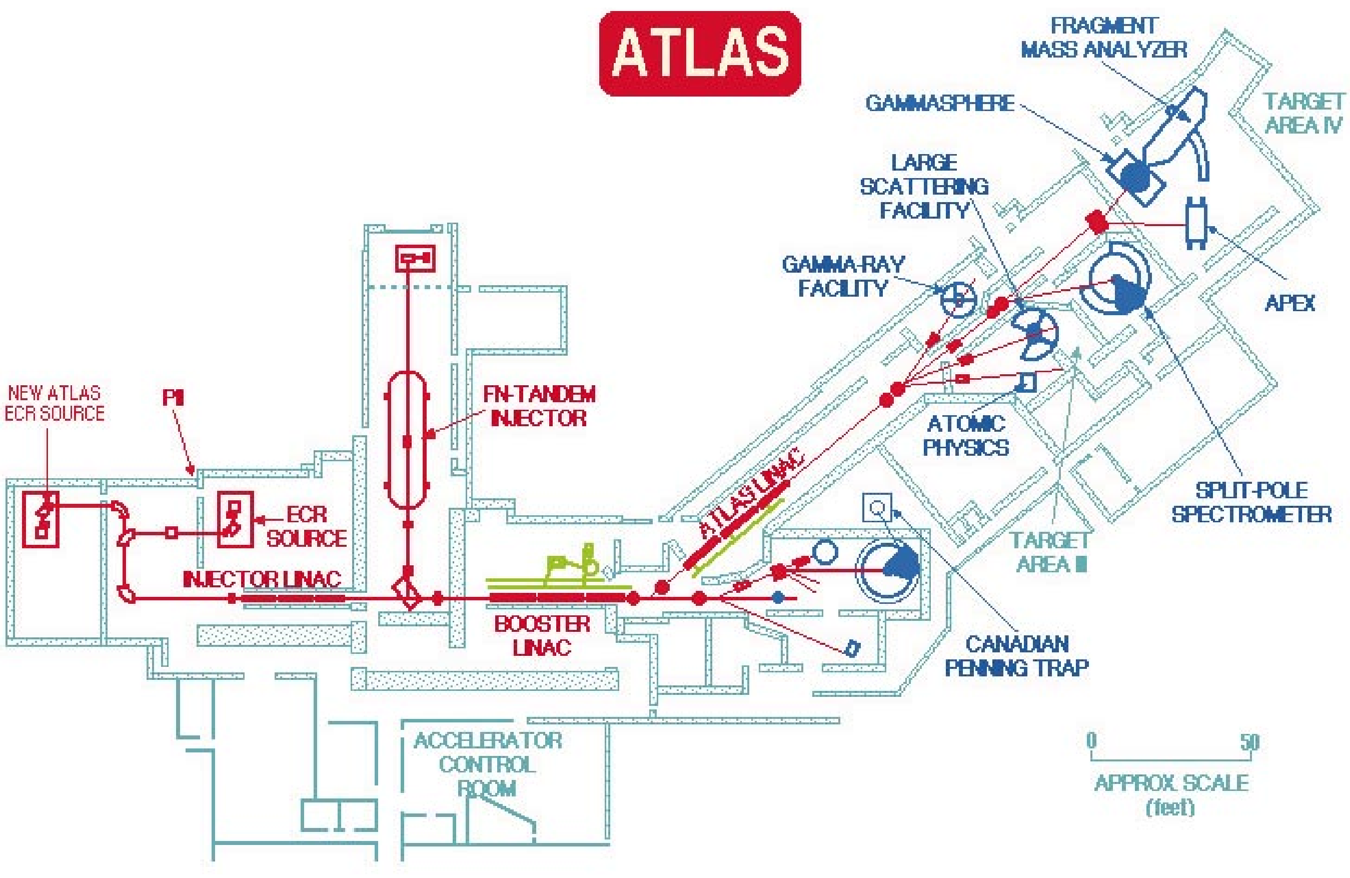

Figure 1. Floor plan of the ATLAS facility. The three major linac sections, as well as the original tandem injector, are indicated.

Since 1978, the facility that would eventually become known as ATLAS [2] (the Argonne Tandem LINAC Accelerating System) has been providing beams of heavy ions to the nuclear physics research program at Argonne. Construction and expansion of the facility has proceeded in parallel with operation of the accelerator for the

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research program. A milestone was reached in 1985 with the dedication of ATLAS as a national user facility for heavy-ion research. A second milestone was passed when the Positive-Ion Injector (PII) linac [3] was commissioned in 1992. Today ATLAS is a national user facility providing over 6000 beam hours each year for research in low-energy heavy-ion nuclear and atomic physics. This is accomplished with a total operating staff of 23 persons. Whereas most accelerator facilities provide beams of one species, usually protons or electrons, ATLAS provided in FY98 26 different isotopes from protons to uranium at hundreds of differing energies with beam quality, as measured by emittance, spot sizes, and energy resolution equaled only by lower-energy tandem electrostatic accelerator facilities.

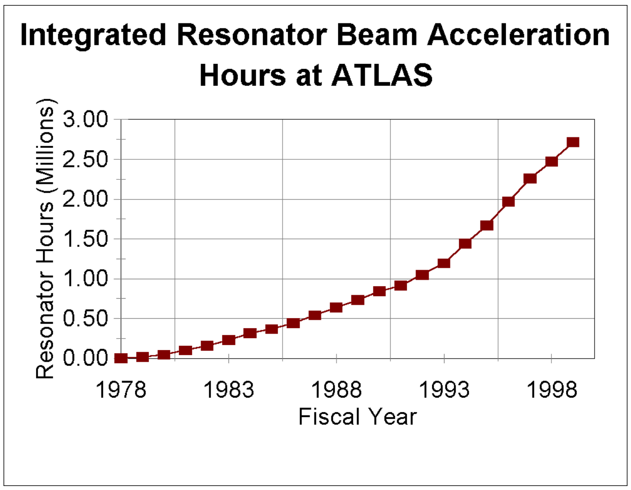

Figure 2. Integrated cavity-hours of operation with beam since first beam was accelerated in ATLAS in 1978.

With over 20 years of operation experience accumulated, ATLAS is the longest running superconducting RF facility in the world. ATLAS has accumulated over 2.8 million resonator-hours of operation with beam during that time, as shown in figure 2. Such a long operating history provides a rich database of experiences to assess the reliability and ruggedness of operation of superconducting resonators, at least for low-beta structures and in a specific operating environment. This paper will review that operating history, describe specific performance levels, and discuss significant operating problems that have arisen during these years of operation.

2 Facility and Resonator Description

The present floor plan of the ATLAS facility is shown in Figure 1. The superconducting heavy-ion linac was first envisioned as an energy 'booster' to heavy-ion beams from a tandem electrostatic accelerator. Today the tandem accelerator serves in parallel with the Positive-Ion Injector linac as one of two injectors to the main ATLAS linac which consists of two distinct sections sections.

The Positive-Ion Injector (PII) is a very-low velocity superconducting linac consisting of 18 resonators distributed among four velocity-match classes from β=0.009 to β=0.037. In total they provide approximately 12 MV of effective accelerating voltage . The resonators are pure niobium four-gap quarter-wave structures [4] with an outer housing of explosively bonded copper to niobium.

Figure 3 shows a cutaway view of the quarter-wave resonators and lists relevant information about each resonator. These resonators were constructed between 1987 and 1991 and have been in, essentially, continuous operation since 1991. The resonators are cooled by liquid helium gravity fed from a reservoir located above the resonators. The available cooling to each resonator is approximately 10 watts each.

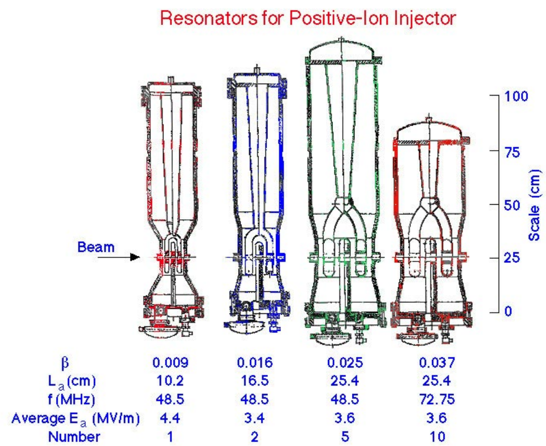

Figure 3. Cutaway view of the quarter-wave four-gap resonators used in the ATLAS Positive Ion Injector. A total of 18 resonators, distributed as indicated, provide 12 MV of accelerating voltage.

The next two linac sections, known as 'Booster' and 'ATLAS', respectively consist of 24 and 18 resonators of the split-ring design. Twelve resonators in the 'Booster' section of the linac are the 'low-beta' class (β=0.06) and the remainder of the resonators are matched to β=0.105. Cutaway views of the two classes of split-ring resonators used in these linac sections along with important system parameters are show in figure 4. The split-ring resonators are of niobium construction with explosively bonded copper and niobium housings.

Cooling of the split-ring resonators is by forced flow of liquid helium to the base of each resonator and through both loading arms and drift tube assemblies. There are a total of 46 split ring resonators in the ATLAS facility, but four function as rebunchers/debunchers for manipulation of the beam phase space. The field requirement for these resonators is generally low and they have not been included in the following discussion.

All ATLAS resonators are cooled to 4.5K by continuously flowing liquid helium from a cryogenic plant with a total capacity of approximately 1100 watts. In addition to the accelerating structures, ATLAS uses iron-shielded superconducting solenoids, a superconducting beamline switching magnet, and four rebunching resonators that must be cooled by the cryogenic system.

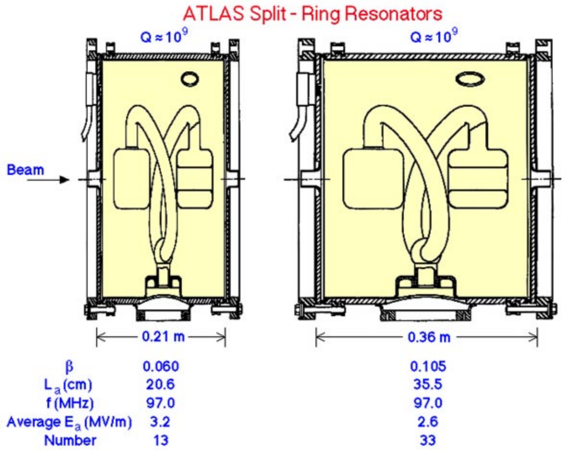

Figure 4. Cutaway view of the ATLAS split-ring resonators used in the 'booster' and 'ATLAS' linac sections of the accelerator. A total of 42 resonators are used for acceleration and 4 are used for bunching and longitudinal phase-space manipulation.

3 Resonator Performance

The history of performance of the ATLAS split-ring resonators extends back as far as 1978, while the first on-line operation of the PII quarter-wave resonators occurred in 1989. Much detailed information of individual resonator performance is available, but in this report I will focus on average performance of the various resonator classes and typical behavior of those classes to various problems.

On-line performance data for the PII quarter-wave resonators dating back to 1993 is shown in figure 5. The plotted values are averages within each velocity class of resonator. An approximately 10% reduction in average performance is seen for most resonator classes since initial installation. This reflects degradation of performance of some but not all resonators in each class. In no case has the average on-line performance met the average for off-line acceptance tests which is indicated in the figure by the column of data labeled 'new'.

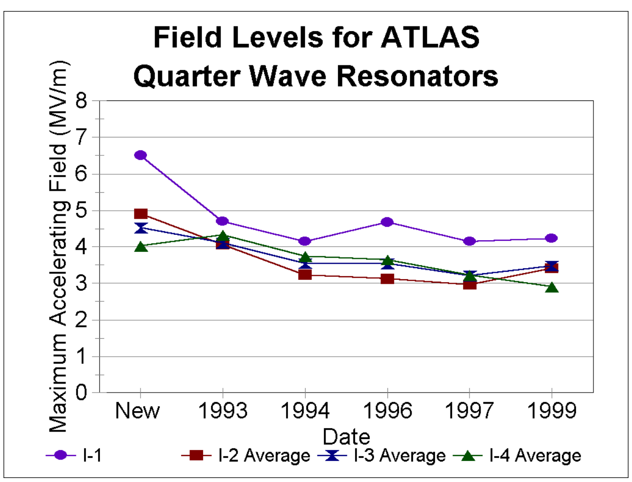

Figure 5. The average on-line operating accelerating fields achieved over a six year period for the PII quarter-wave resonators. Note that there is only one low-velocity I-1 resonator. The column identified as 'New' is the average final off-line acceptance test results for each set of resonators.

On-line performance data for the ATLAS split-ring resonators dating back to 1982 is shown in figure 6. The plotted values are averages for the two velocity classes, but the β=0.1 'high-beta' resonators are divided into two groups in the figure. Resonators in the group identified as 'High Beta-1', along with the 'low-Beta' resonators, are the longest serving resonators in ATLAS. Some of those units were constructed in the late 1970's. Resonators in the group identified as 'High Beta-2' generally date back to 1985.

For the split-ring resonators, one again sees that the off-line acceptance test performance significantly exceeds the on-line performance. In the case of the low-beta resonators, on-line performance has slowly improved to the point where present on-line performance significantly exceeds the initial on-line behavior. The low-beta resonators now average 3.5 MV/m accelerating field and surface fields over 16 MV/m.

The high-beta resonator performance is essentially unchanged since 1985, averaging 2.6 MV/m accelerating field or 13 MV/m surface field. There has been no deterioration over time for the average performance. The history of individual resonators does show some specific damage due to significant events such as catastrophic vacuum accidents.

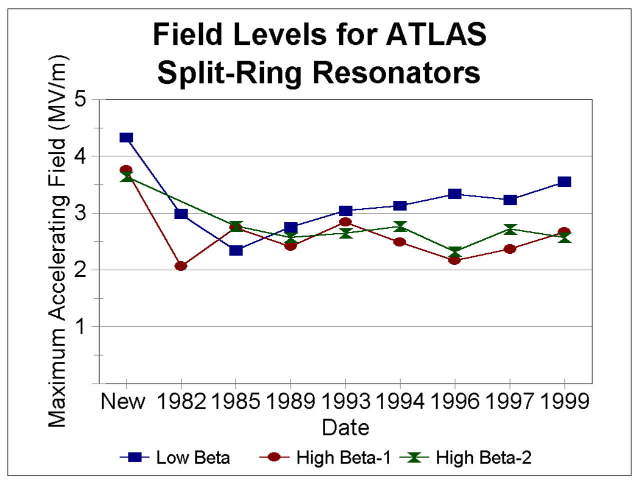

Figure 6. The average on-line operating accelerating fields obtained with the ATLAS split-ring resonators since 1982. The column identified as 'New' is the average final off-line acceptance test results for each set of resonators.

The difference between online resonator performance and the performance observed during the offline acceptance tests are likely to arise from three effects. First, significantly greater helium cooling capacity is available in the off-line test station than is available online. This is especially true for the split-ring resonators. The online cryostat cooling capacity was designed to provide an average of 4 watts cooling at 4.5K to each resonator. In general 8 watts is the maximum cooling available to any one split-ring resonator. The PII quarter-wave resonators do not have such a stringent limitation since each is gravity fed from a common reservoir, but there is a total capacity limit which imposes some restrictions.

Second the offline test system employs a variable rf drive coupler which allows better power delivery during resonator conditioning. Thus it is possible to better condition offline resonators with high-power rf processing.

Finally the offline tests are performed without the voltage-controlled reactance (VCX) phase stabilization assembly attached. Early resonator performance was limited by the VCX system for the best performing resonators. This situation has largely been solved and the most recent years do not reflect any significant limitations to the VCX system. A large part of the improvements in performance of the low-beta split-ring resonators shown in figure 6 is due to improvements in the performance of the VCX system.

Another aspect of resonator performance is failures which make the resonator either inoperable or forces operation at reduced fields. Examples of such failure modes are weld failures or stress related cracks not associated with welds. The housing of both the split-ring and the quarter-wave resonators is niobium explosively bonded to copper. The differential contraction experienced between these two metals during cooling can cause significant stresses, especially in geometrically complex regions of the housing such as port penetrations.

In 1986, after eight years of operation, cracks in the niobium outer housing at the VCX ports (see Figure 4) began to appear in a few resonators. The breaks were repaired by electron-beam welding. Additional copper was removed near the port to reduce the stresses from differential contractions. This problem eventually appeared in seven split-ring resonators. The repair was completely successful in all cases and a program to remove additional copper from the VCX port regions of all split-ring resonators was undertaken. No additional cracking has been observed since 1995.

In addition to the stress-related cracks described above, two quarter-wave resonators experienced weld failures in the internal center drift-tube in 1996. Repair of these units was completely successful.

4 Resonator Operating Issues

For successful operation of a facility based on rf superconductivity, other aspects of resonator operation can be as important as field performance and catastrophic failure modes. Significant lost time can result from issues such as multipacting, field degradation, electronics failures, and resonator vibration. Understanding the source of lost operating time is crucial to the success of a user-based facility. At ATLAS these problems are controlled sufficiently to allow the overall facility to achieve over 6000 hours per year of operation with a reliability factor of over 90%. In total resonators and associated rf electronics systems cause 16% of all lost time at ATLAS in FY1998 as seen in figure 7. The distribution of that lost time among subsystems is shown in figure 8.

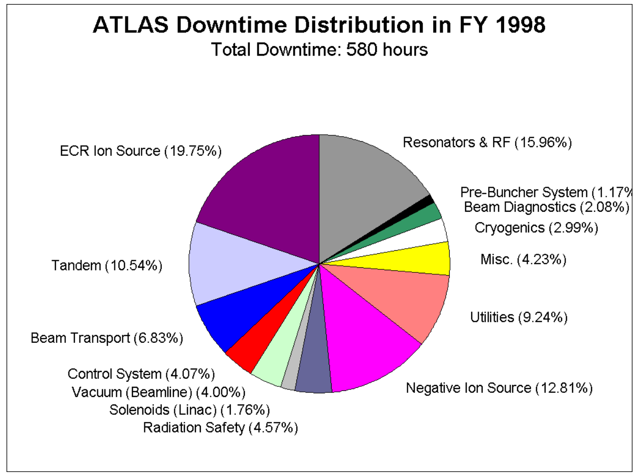

Figure 7. Distribution of causes of down-time at ATLAS in FY1998 (6050 hours total operating time).

The low-velocity resonators used at ATLAS do experience multipacting. After initial cooldown a burn-in time of 4-6 hours is required to remove all multipacting barriers in a resonator. After initial burn through of the barrier, multipacting may reoccur due to a variety of processes. The reoccurrence of multipacting barriers and their subsequent reprocessing account from 40% of the lost time due to resonators at ATLAS. This time has been significantly reduced with the installation of new control modules, which have sufficient gain to burn through multipacting barrier without external electronics. Poor beamline vacuum conditions in certain regions are a major cause of restoration of multipacting barriers.

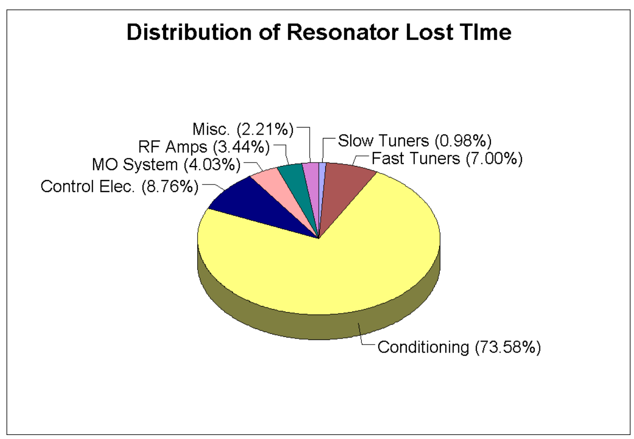

Figure 8. Distribution of system failures related to resonators which comprise 16% of all lost time at ATLAS.

Degradation of maximum rf field performance sometimes occurs and requires high-power rf conditioning to restore the original performance. Typically 30 to 45 minutes are lost with each such event. Occasionally additional lost time occurs due to the ‘soft nature’ of the failure. That is operation can sometimes be restored by various ‘tricks’. These tricks may eventually fail and the integrated lost time from such evolutionary decisions adds to the total lost time. For the present operations, field degradation accounts for approximately 35% of the lost time due to resonators at ATLAS, about 5% of the total lost time.

The ability to control resonator phase sufficiently accurately is still, to some extent a developmental problem. The sensitivity of a resonator to vibrations determines the amount of reactive power which the phase control system must handle. For ATLAS this very difficult problem was solved with a Voltage Controlled Reactance (VCX) system [7,8] which slightly shifts the instantaneous resonator frequency under electronic feedback control. For ATLAS resonators a frequency shift, or control window, of approximately 200 Hz is sufficient for phase control. It is possible to develop sources of vibration in the facility which cause a resonator to shake in such a manner that the control window of the VCX system is exceeded. This problem is now quite infrequent at ATLAS, causing less than 2% of the lost time assigned to resonators. Failure of a PIN switching diode in the system or failure of the switching electronics is a larger source of downtime. The entire facility experiences a failure rate of 1 or 2 PIN diodes per month. Each resonator operates with 10 diodes in parallel. Blowing a fuse to disconnect a failed diode requires approximately 15 minutes in order to restore operation.

The failure of electronics associated with resonators constitute a total of 23% of the lost time due to resonators at ATLAS. Failures of the VCX electronics account for 7% and the remainder of the lost time is equally distributed between, rf amplifiers, control modules, the master-oscillator system, and computer interfaces.

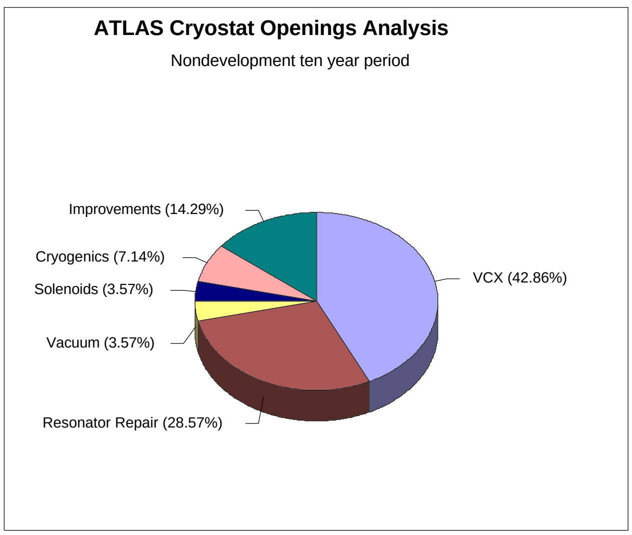

Figure 9. Distribution of primary causes for cryostat openings over a ten year, non-developmental period at ATLAS.

The use of independently phased resonators in the ATLAS design not only allows the best use of the available rf accelerating fields but also allows great flexibility in working around major failures, which would otherwise require opening a cryostat for repair. Excluding major upgrade periods, an average of 2.7 cryostat openings per year has been required at ATLAS over the past 15 years. The frequency of subsystem failures requiring cryostat openings is shown in figure 9. The largest single reason for cryostat opening is to repair the PIN diode VCX system. Improvements to the design of that system have significantly reduced the failure rate in the past few years.

Over twenty years of operating experience with rf superconductivity at ATLAS has demonstrated that it is a robust, reliable, cost-effective technology. To make use of rf superconductivity a number of innovative design concepts for heavy-ion linacs were necessary. These new approaches have resulted in a facility which today is unparalleled in flexibility and beam quality. New concepts for radioactive isotope acceleration [9] continue to expand on the ATLAS technology and show that ATLAS is still at the forefront of ion acceleration.

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5 References

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